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(54) **METHOD FOR THE REDUNDANCY-OPTIMIZED PLANNING OF THE OPERATION OF A MOBILE ROBOT**

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(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,954,962 A * 9/1990 Evans, Jr. G05D 1/0274
701/28
5,413,454 A * 5/1995 Movsesian B25J 5/007
294/100

(Continued)

FOREIGN PATENT DOCUMENTS

DE 10229293 A1 1/2004
DE 102011106321 A1 1/2013

(Continued)

OTHER PUBLICATIONS

European Patent Office; Search Report and Written Opinion in International Patent Application No. PCT/EP2016/062918 published Sep. 14, 2016; 12 pages.

(Continued)

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(57) **ABSTRACT**

A method for redundancy-optimized planning of the operation of a redundant mobile robot having a robot arm includes using a tool center point (TCP) associated with the robot arm and assigned a Cartesian TCP coordinate system having a first, second, and third TCP-coordinate axes; using a Cartesian world coordinate system having first, second, and third world coordinate axes, wherein the first and second world coordinate axes span a plane on which the mobile robot moves, a height of the TCP from which the plane is assigned, and one of the TCP coordinate axes and the plane enclose an angle; creating at least one graph wherein a redundancy is presented as a function of the height and the angle, wherein

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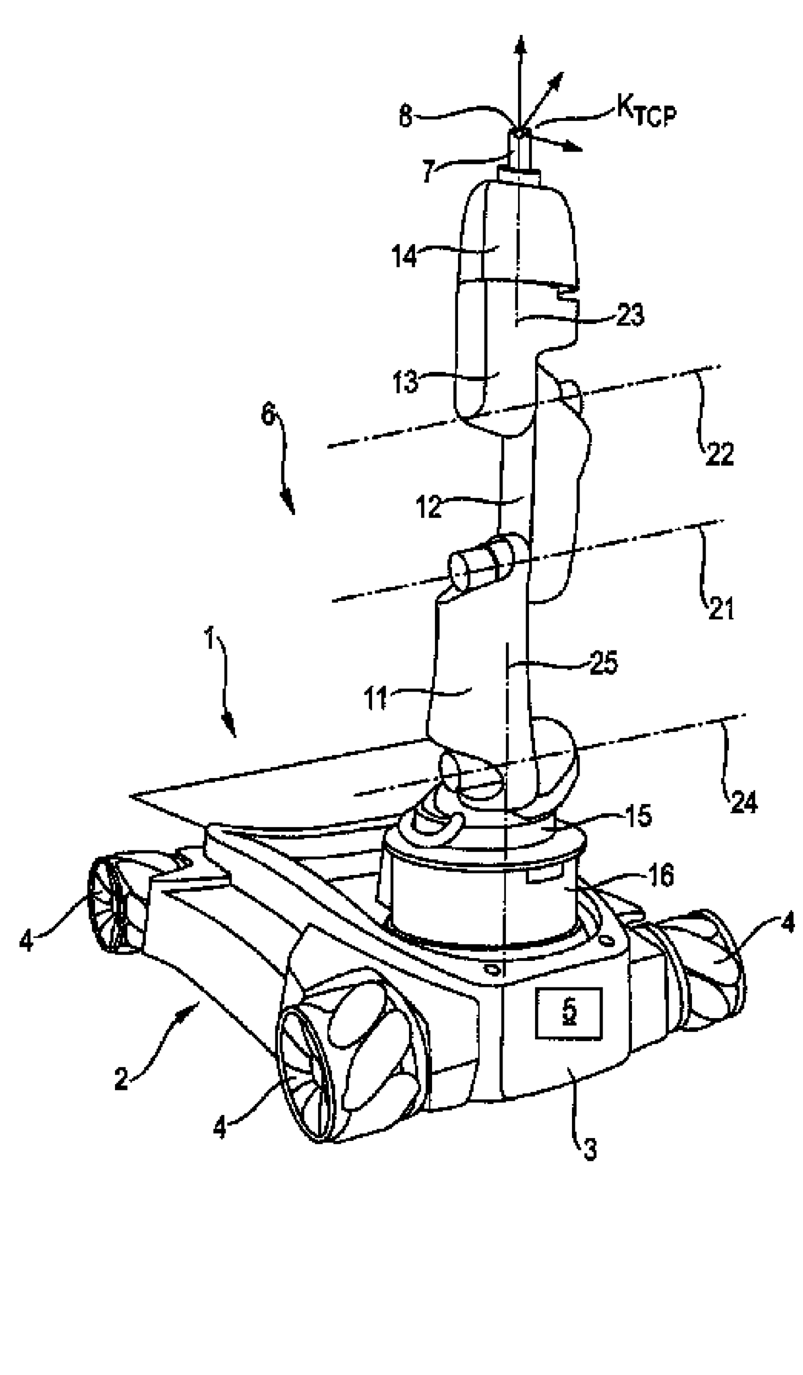

the redundancy is a measure of possible configurations of the mobile robot depending on the height and the angle; and planning operation of the mobile robot using the graph.

12 Claims, 6 Drawing Sheets

(58) **Field of Classification Search**
USPC 700/245, 247, 250, 251, 253, 262, 263; 901/1, 2, 14, 16, 46; 318/568.11, 568.1, 318/568.13, 568.15, 568.21, 568.22; 701/23, 25
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,550,953	A	8/1996	Seraji	
7,756,606	B2	7/2010	Nakajima et al.	
2011/0224815	A1 *	9/2011	Sonner	B25J 9/1664 700/97
2013/0103192	A1 *	4/2013	Huettenhofer	B25J 9/162 700/245
2013/0310982	A1 *	11/2013	Scheurer	B25J 9/1664 700/263

FOREIGN PATENT DOCUMENTS

DE	102011084412	A1	4/2013
DE	102012208094	A1	11/2013
EP	2485875	B1	4/2013
EP	2664420	A2	11/2013

OTHER PUBLICATIONS

German Patent Office; Office Actio in related German Patent Application No. 10 2015 211 865.7 dated Oct. 26, 2015; 4 pages.

Patel Sarosh et al; Publication entitled“Manipulator Performance Measures—A Comprehensive Litertaure Survey” published Feb. 15, 2014; 39 pages.

* cited by examiner

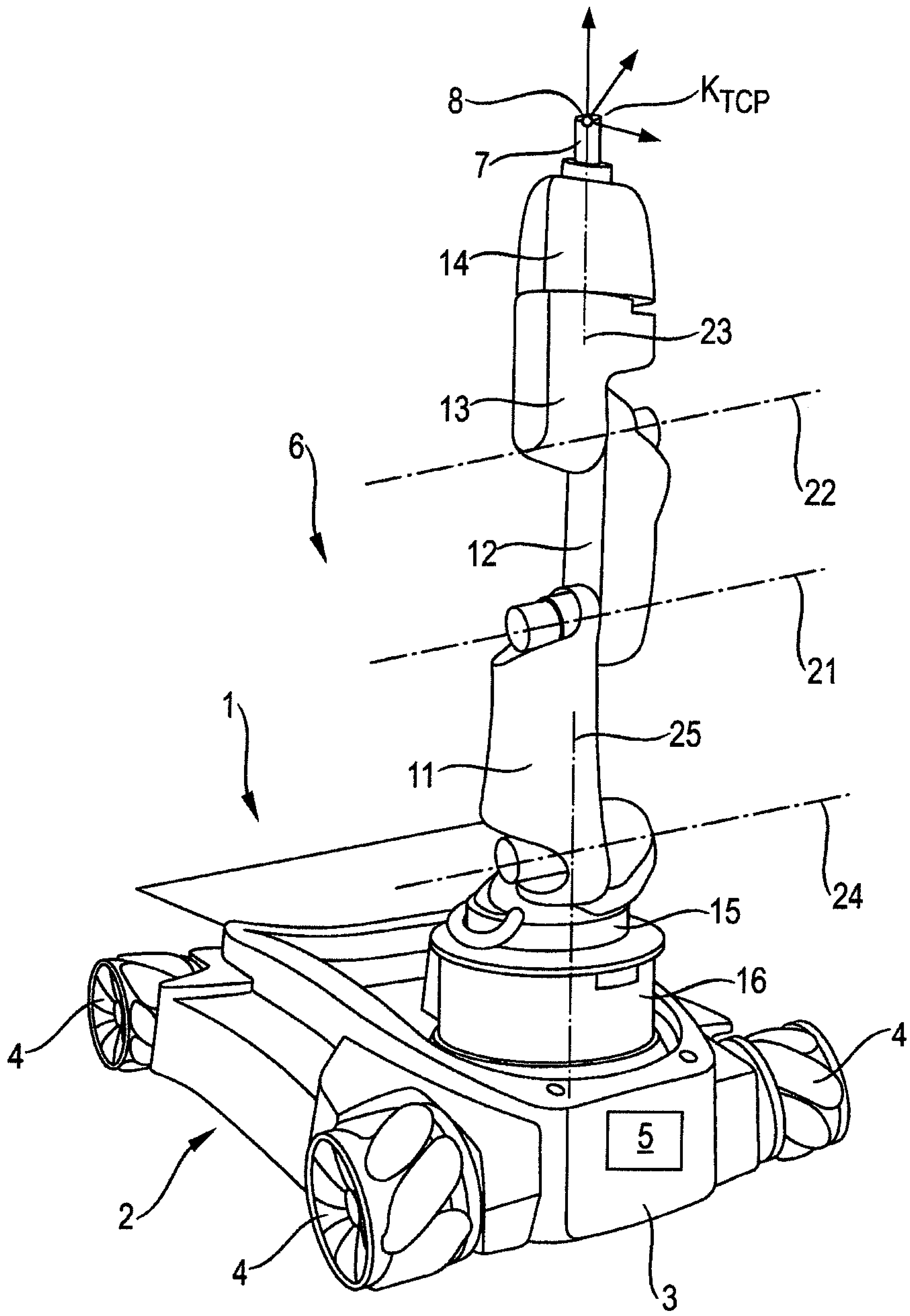

FIG. 1

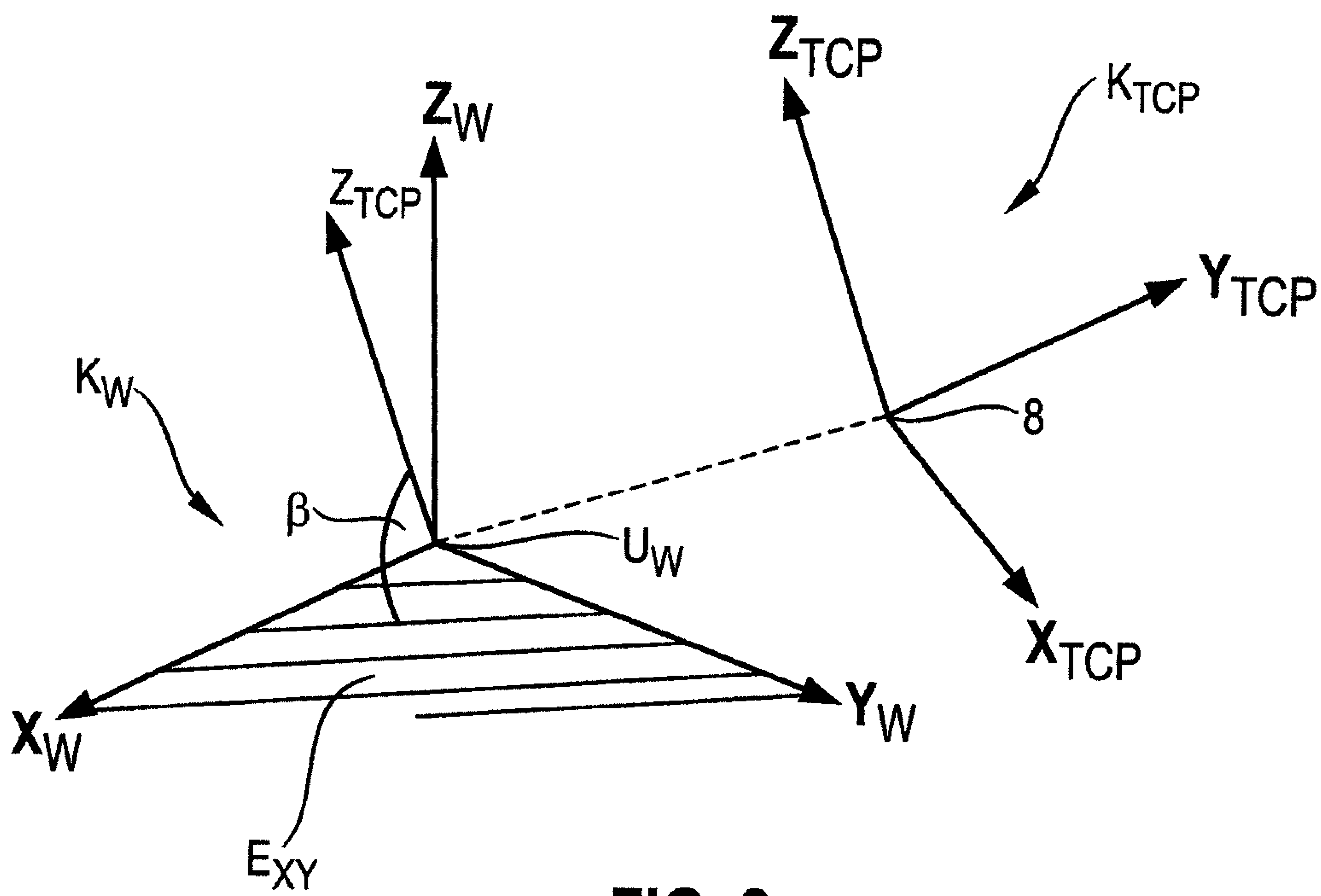

FIG. 2

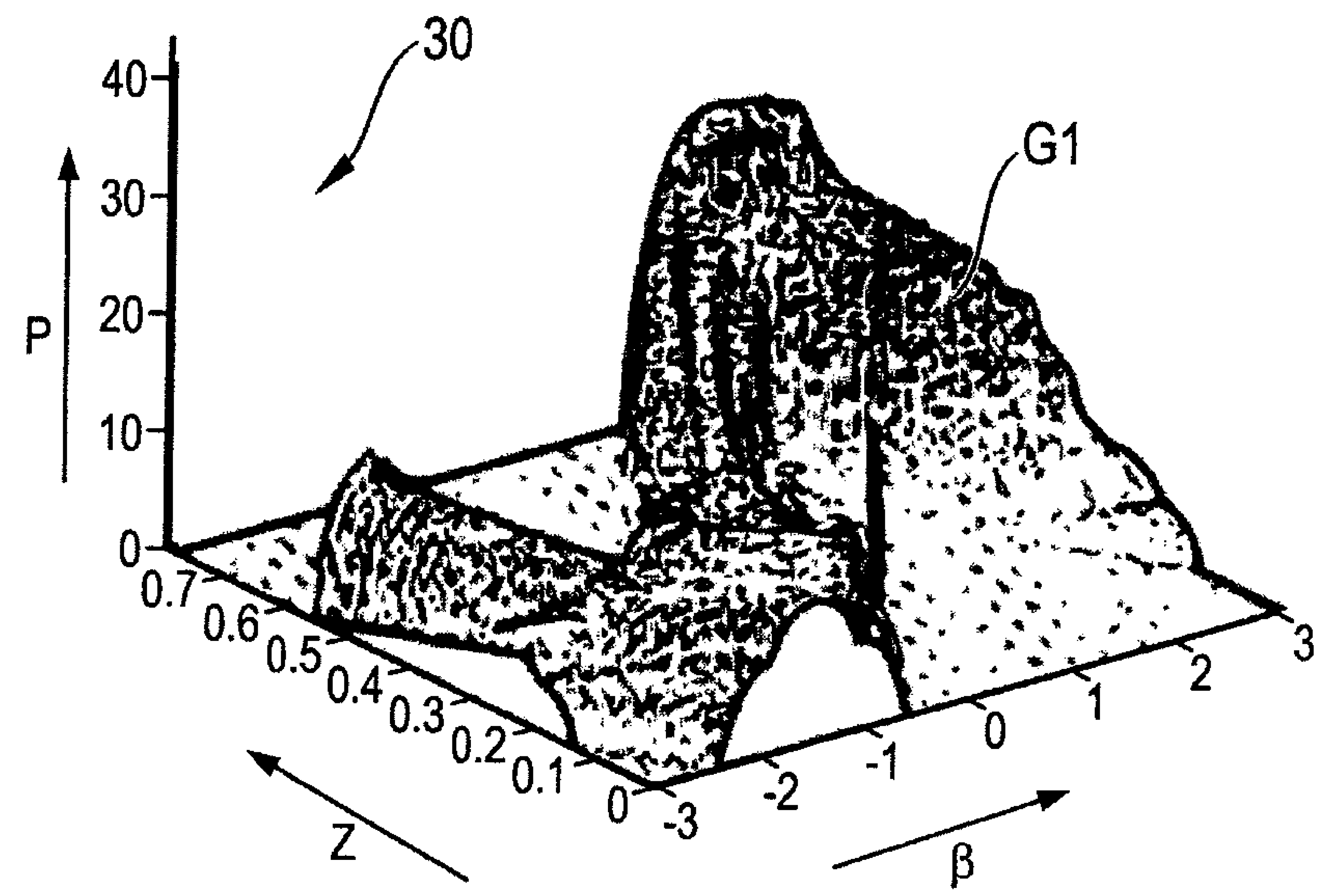
30
G1
P
40
30
20
10
0
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Z
-3
-2
-1
0
1
2
3
β

FIG. 3

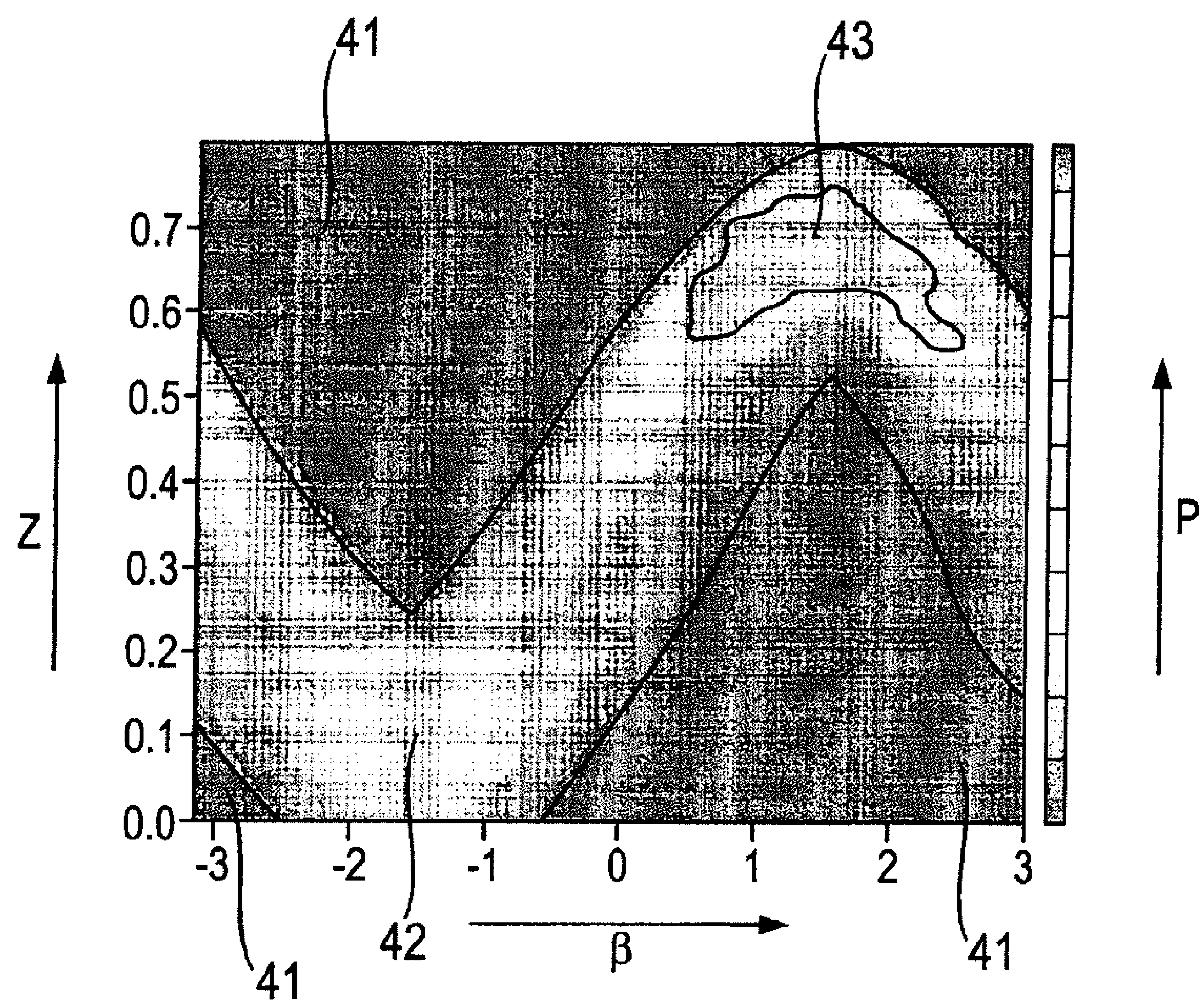
41
43
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Z
P
-3
-2
-1
0
1
2
3
β
41
42
41

FIG. 4

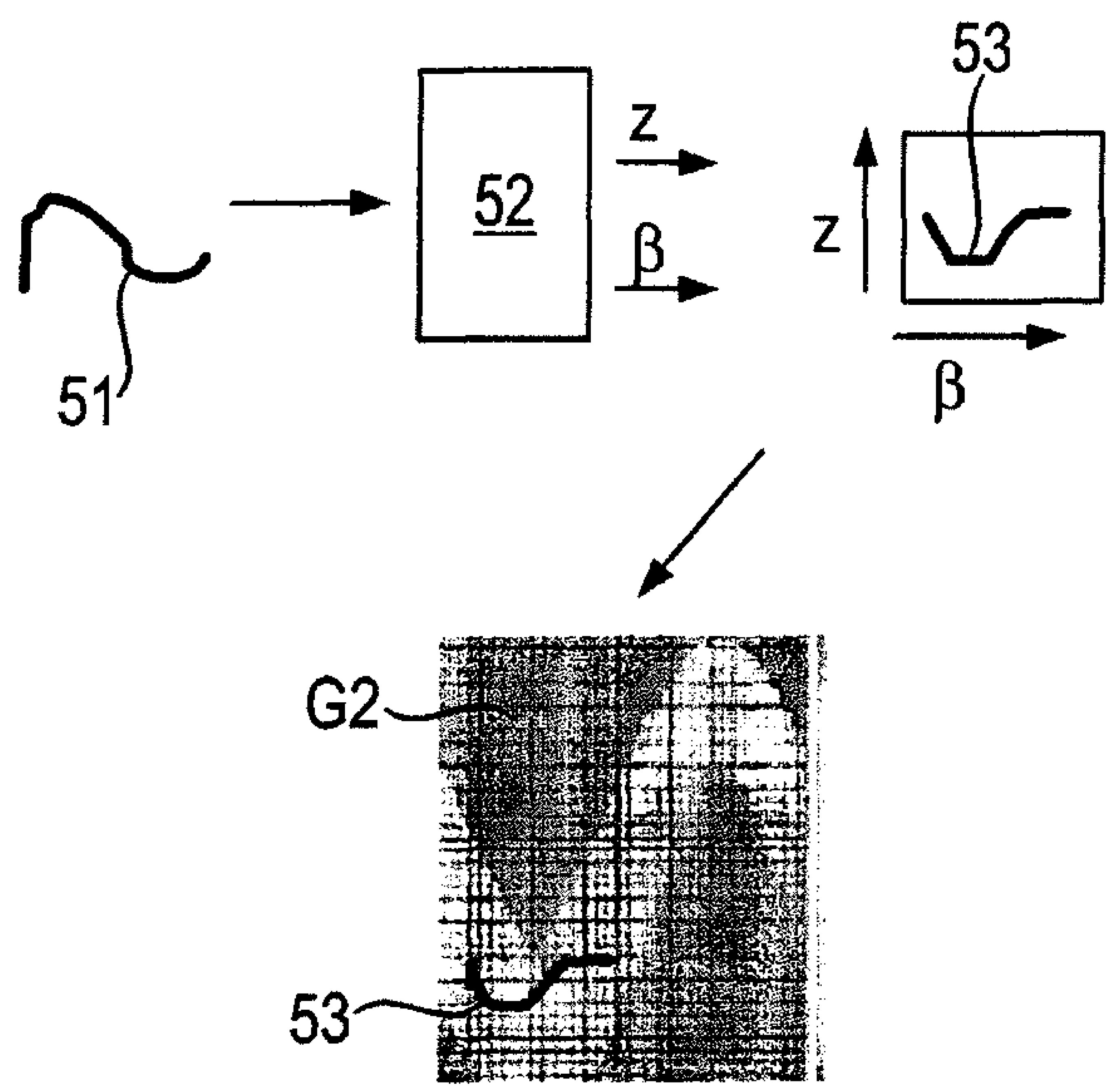

FIG. 5

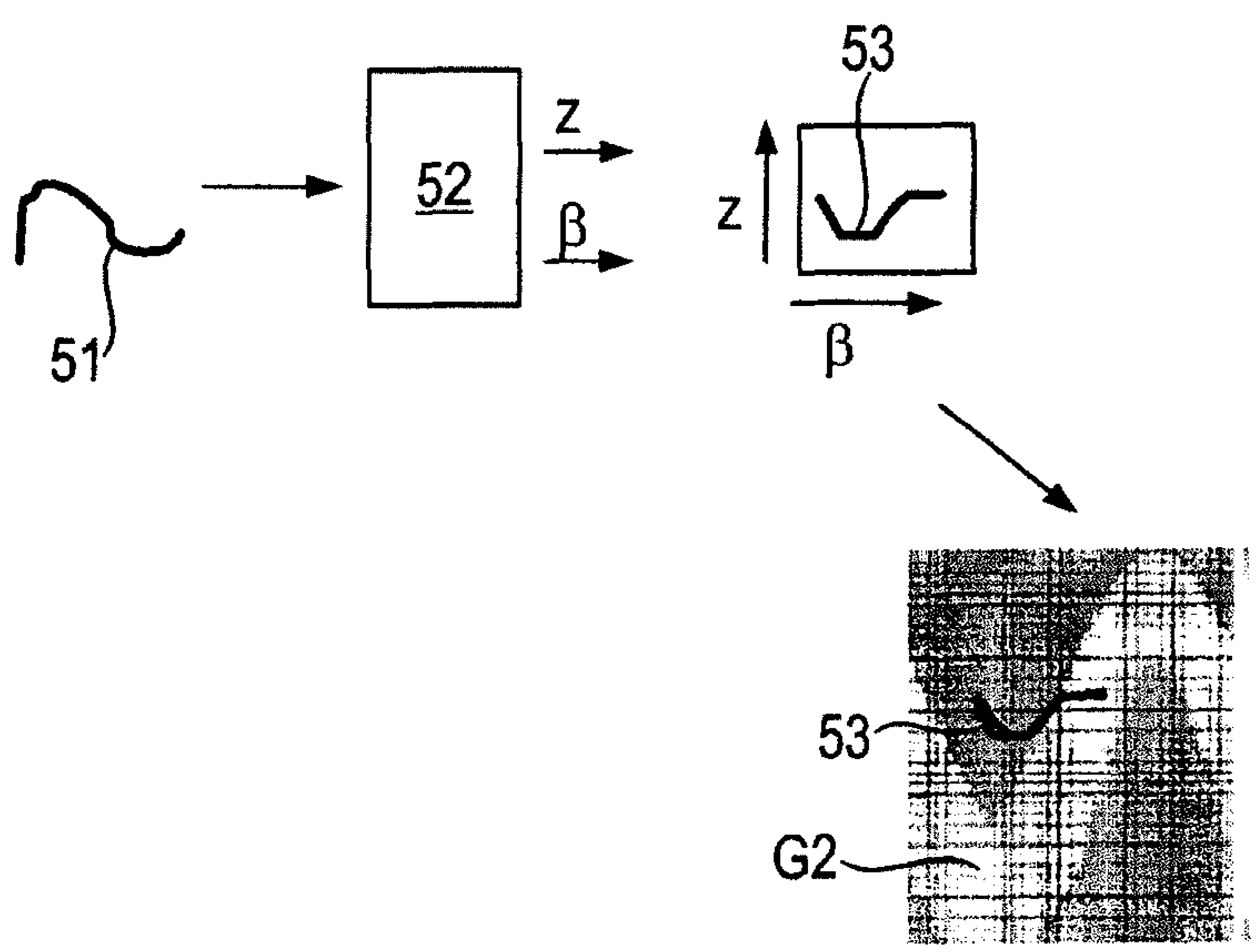

FIG. 6

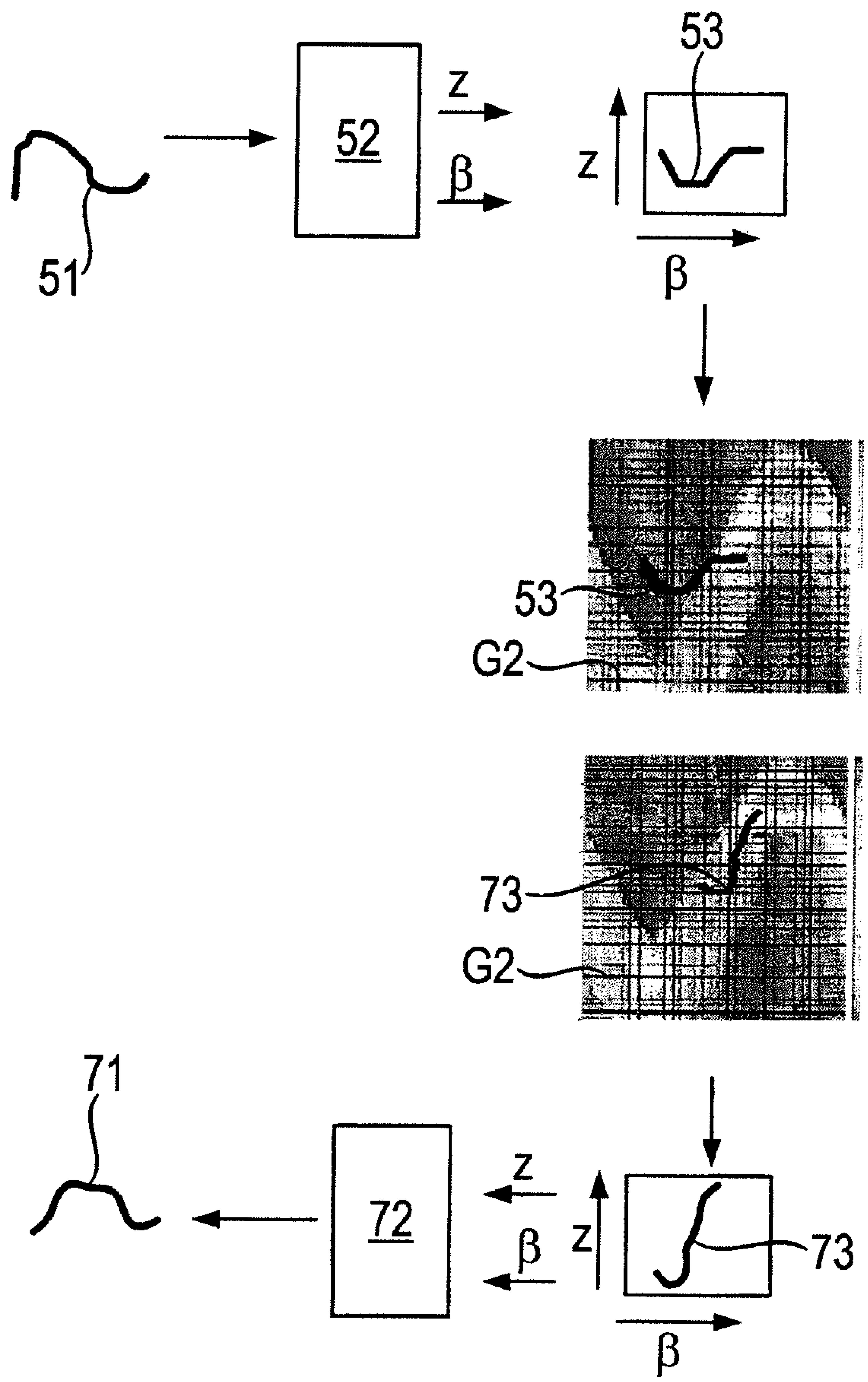

FIG. 7

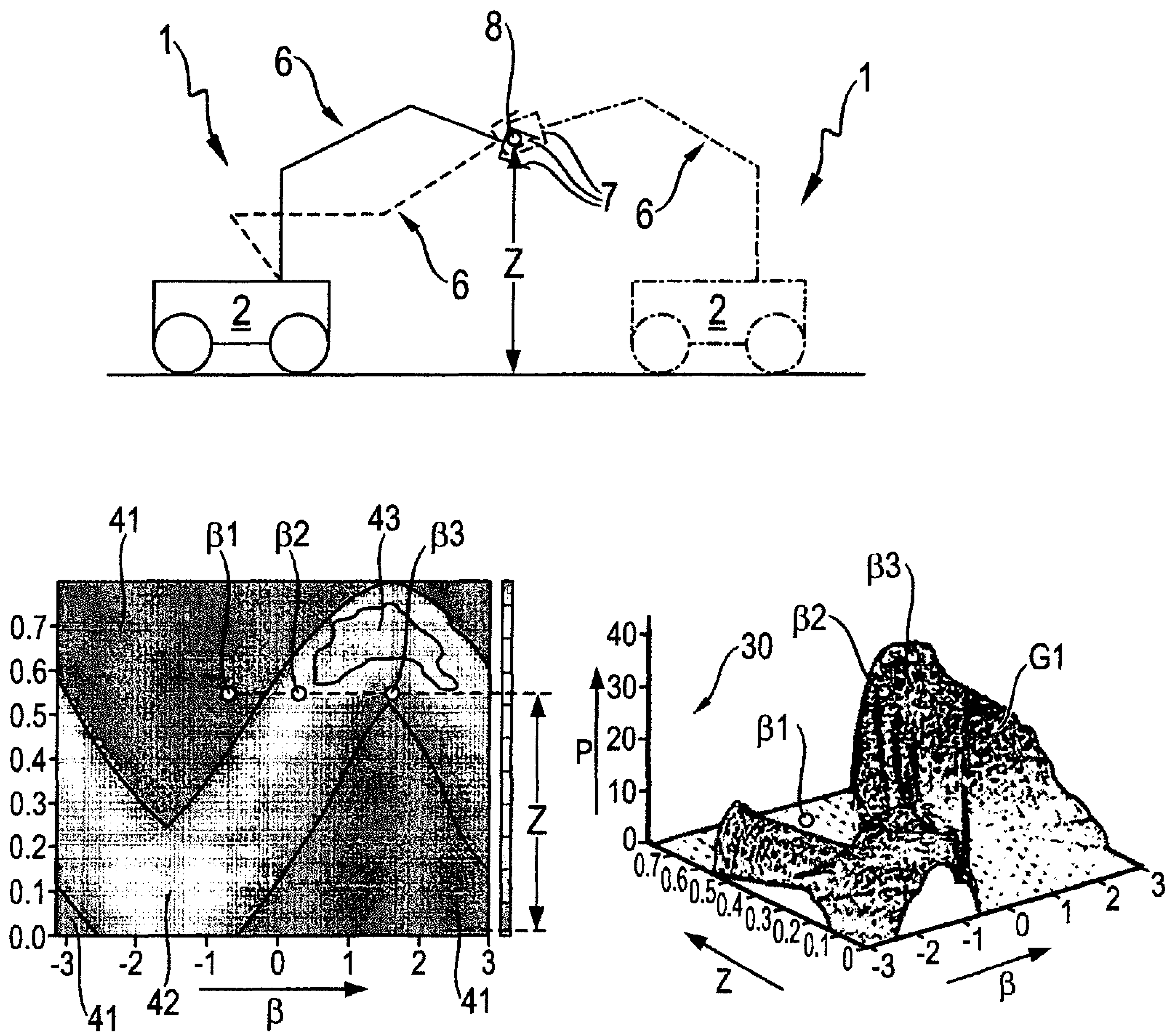
1
6
8
7
6
1
6
Z
2
2
41
β1
β2
43
β3
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-3
-2
-1
0
1
2
3
41
42
β
41
Z
β3
β2
G1
40
30
20
10
0
30
P
β1
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-3
-2
-1
0
1
2
3
Z
β

FIG. 8

METHOD FOR THE REDUNDANCY-OPTIMIZED PLANNING OF THE OPERATION OF A MOBILE ROBOT

CROSS-REFERENCE

This application is a national phase application under 35 U.S.C. § 371 of International Patent Application No. PCT/EP2016/062918, filed Jun. 7, 2016 (pending), which claims the benefit of German Patent Application No. DE 10 2015 211 865.7 filed Jun. 25, 2015, the disclosures of which are incorporated by reference herein in their entirety.

TECHNICAL FIELD

The invention relates to a method for the redundancy-optimized planning of the operation of a mobile robot.

BACKGROUND

U.S. Pat. No. 5,550,953 discloses a mobile robot and a method for operating the mobile robot. The mobile robot comprises a robot arm with several members, which are movable relative to each other, and a carrier vehicle to which the robot arm is fastened.

SUMMARY

The object of the invention is to provide an improved method for planning the movement of a mobile robot. The object of the invention is achieved by a method for redundancy optimized planning of an operation of a redundant mobile robot, which is connected to a mobile carrier vehicle, a robot arm with several members connected via joints, pivotable mounting with respect to axes of rotation, drives for moving the members relative to each other, and an electronic control device which is arranged to control the drives for the members and the carrier vehicle for the movement of the mobile robot, comprising the following method steps:

Use of a tool center point that is assigned to the robot arm, assigned Cartesian TCP coordinate system with a first TCP coordinate axis, a second TCP coordinate axis and a third TCP coordinate axis,

Using a Cartesian world coordinate system having a first world coordinate axis, a second world coordinate axis and a third world coordinate axis, whereby the first world coordinate axis and the second world coordinate axis span a plane, on which the mobile robot moves, a height of the tool center point from the plane of the third world axis is assigned, and one of the TCP coordinate axes and the plane enclose an angle,

Creating at least one graph in which a redundancy is presented as a function of the height and the angle, whereby the redundancy is a measure of possible configurations of the mobile robot depending on the height and angle, and

Planning an operation of the mobile robot with the help of the least one graph.

The mobile robot is a redundant mobile robot, for which there are generally several possible configurations of the mobile robot for the respective positions and orientations of the tool center point in space. The configuration of the mobile robot entails that for the respective positions and orientations of the tool center points there are several possible positions and orientations of the robot arm and several possible positions of the carrier vehicle in the plane.

The positions of the robot arm arise from the angular positions of the individual members relative to each other.

There are thus generally redundant configurations of the mobile robot for the individual positions and orientations of the tool center point in space. The positions and orientations can be expressed, for example, in the world coordinate system. The orientation of the tool center point can also be expressed in coordinates of the TCP coordinate system.

According to a preferred implementation of the invention, the robot arm comprises exactly five degrees of freedom and thus has as members a first member, a second member, a third member, a fourth member, a fifth member and a sixth member, and as axes of rotation a first axis of rotation, a second axis of rotation, a third axis of rotation, a fourth rotation axis of rotation and a fifth axis of rotation. In this case, the mobile robot has in particular eight degrees of freedom because the carrier vehicle comprises three degrees of freedom.

Preferably, the first axis of rotation, the second axis of rotation and the fourth axis of rotation are horizontal, and the fifth axis of rotation is vertical. In particular, the second member is pivotable relative to the first member with respect to the first axis of rotation, the second member is followed by the third member, the third member is pivotable relative to the second member with respect to the second axis of rotation, the fourth member is pivotable relative to the third member with respect to the third axis of rotation, which is perpendicular to the second axis of rotation, and it comprises a fastening device for fastening a tool or the tool, the sixth member is mounted immovably on the carrier vehicle or represents the carrier vehicle, the fifth member is pivotable relative to the sixth member with respect to the fifth axis of rotation, and the first member is pivotable relative to the fifth member with respect to the fourth axis of rotation. Preferably, the third TCP coordinate axis extends in the direction of the third axis of rotation and encloses an angle with the plane.

The robot arm can also have four degrees of freedom. Then, the robot arm comprises a first member, a second member, a third member, a fourth member, and a fifth member, and as axes of rotation, a first axis of rotation, a second axis of rotation, a third axis of rotation and a fourth axis of rotation. In particular, the first rotation axis, the second axis of rotation and the fourth axis of rotation are horizontal. In particular, the second member is pivotable relative to the first member with respect to the first axis of rotation, the second member is followed by the third member, the third member is pivotable relative to the second member with respect to the second axis of rotation, the fourth member is pivotable relative to the third member with respect to the third axis of rotation, which is perpendicular to the second axis of rotation, and it comprises a fastening device for fastening a tool or the tool, the fifth member is mounted immovably on the carrier vehicle or represents the carrier vehicle. Preferably, the third TCP coordinate axis extends in the direction of the third axis of rotation and forms an angle with the plane.

The mobile carrier vehicle preferably comprises wheels and drives for driving the wheels. Preferably an electronic control device has been set up to control the drives for the wheels to move the carrier vehicle.

The carrier vehicle may also comprise legs or be implemented as a magnetic levitation transport vehicle.

The carrier vehicle is preferably implemented as an omni-directionally movable carrier vehicle (holonomic platform). Preferably therefore, the wheels of the carrier vehicle are implemented as omnidirectional wheels. An example of an omnidirectional wheel is known to professionals as the Mecanum wheel. Due to the omnidirectional wheels, the mobile robot or its carrier vehicle according to the invention, can move freely in space. Thus the carrier vehicle can not only move forward, backward or sideways or along curves, but it can for example also rotate around a vertically oriented axis.

According to the invention, at least one graph is used, in which the redundancy is presented as a function of the height and the angle, whereby the redundancy is a measure for possible configurations of the mobile robot depending on the height and the angle. This makes it possible to relatively easily visualize the possible configurations of the mobile robot inter alia for the height of the tool center point, thereby simplifying the planning of the operation of the mobile robot.

The at least one graph, for example, is a first graph, whereby the height, the angle and the redundancy form a three dimensional cartesian coordinate system in which the redundancy is depicted as a function of the height and angle as the first graph. This results in a graphic mountain range, in which it is possible to quite easily read the different heights of the tool center point and the angle.

Preferably, the redundancy in the first graph is marked differently in color or grayscales.

According to a preferred implementation of the method according to the invention, the at least one graph is a second graph, in which the height is depicted as a function of the angle, and the redundancy in the second graph is marked differently, in particular with a different color or by means of grayscales, to represent the redundancy as a function of the height and angle. The second graph is a two-dimensional graph in which preferably the height and the angle are plotted along corresponding coordinate axes, which are orthogonal.

The second graph shows in particular the height as a function of the angle. To visualize the redundancy, the second graph is marked differently, for example by using different colors or different grayscales to visualize the redundancy. The second graph is in particular a plan view of the first graph. In the second graph it is relatively easy to determine possible (Z; β) pairs or (Z; β) pairs with relatively high redundancy.

The method according to the invention may include the following additional method steps:

Planning a trajectory of a track in six-dimensional space, along which the tool center point is to move automatically,

Transforming the trajectory of the planned path in a two-dimensional subspace, whereby the trajectory of a transformed path is created, whereby the subspace represents the planned position and orientation of the tool center point in height and angle,

Overlaying the trajectory of the transformed planned path with the second graph, and

on the basis of the superimposed trajectory of the transformed track with the second graph, determining whether the planned trajectory can be followed by the mobile robot.

Planning within the six-dimensional space is carried out in particular in coordinates of the world coordinate system (world coordinates) and possibly also in the TCP coordinate system.

If the planned trajectory cannot be followed by the mobile robot, the following method steps can be performed:

Change the trajectory of the transformed planned path within the superimposed second graph, so that a revised trajectory of the transformed planned path is created, which the mobile robot can follow, and

Create a revised planned trajectory in six-dimensional space, based on the revised trajectory of the transformed planned path.

The method according to the invention may include the following additional method steps:

Defining a height for the tool center point

With the aid of the first graph and/or the second graph, determining possible values of the angle,

Determining the value of the angle, to which the highest redundancy is assigned, and

Using the determined value of the angle for planning the movement of the mobile robot.

Alternatively, the method according to the invention may comprise method steps:

Determining an angle,

With the aid of the first graph and/or the second graph, determining possible values of the height,

Determining the value of the height, to which the highest redundancy is assigned, and

Using the determined value of the height for planning the movement of the mobile robot.

When determining the value of the angle or the height, to which the highest redundancy is assigned, it is possible to consider at least one further constraint, such as avoiding collisions of the mobile robot with an object or a safety distance of the mobile robot to an object.

By means of the at least one graph, it is also possible to plan the following task for the mobile robot: The mobile robot is to use a tool implemented as a gripper to grip a workpiece and place it in another position. By means of at least one graph it is possible to determine favorable positions for this task.

BRIEF DESCRIPTION OF THE DRAWINGS

Implementation examples of the invention are shown in the attached schematic drawings.

FIG. **1** depicts a mobile robot, which comprises a carrier vehicle and a robot arm affixed to the carrier vehicle,

FIG. **2** depicts a world coordinate system and a TCP coordinate system

FIGS. **3**, **4** depict respectively one graph,

FIGS. **5**, **6** depict an illustration for checking the trajectory of a planned path,

FIG. **7** depicts an illustration for revising the trajectory of a planned path, and

FIG. **8** depicts an illustration for planning a configuration for the mobile robot.

DETAILED DESCRIPTION

FIG. **1** shows a mobile robot **1**, which in the case of the present embodiment example exhibits an omnidirectional mobile carrier vehicle **2**. This example comprises a vehicle base frame **3** and several wheels **4** pivotably arranged on the vehicle base frame **3**, which are implemented as omnidirectional wheels. In the case of the present implementation example, the carrier vehicle **2** exhibits four omnidirectional wheels **4**. Preferably all wheels **4** are driven by one drive each. The drives, not shown in detail here, are preferably electric drives, in particular controlled electric drives, and are connected to a control device **5** which can, for example, be arranged in or on the vehicle base frame **3**, whereby the control device is set up to control the drives so that these can move the wheels.

An example of an omnidirectional wheel is the so-called Mecanum wheel. In the present implementation example, each of the wheels **4** implemented as omnidirectional or Mecanum wheels exhibits two rigidly interconnected wheel discs, between which several rolling elements are pivotably mounted with respect to their longitudinal axes. The two wheel discs can be pivotably mounted with respect to a rotational axis, and can be driven by one of the drives of the carrier vehicle **2** in such a way that the two wheel discs rotate with respect to the axis of rotation.

The omnidirectional wheels **4** allow the mobile robot **1** or its carrier vehicle **2** to move freely on a plane or a ground, which is not shown in detail. Thus the carrier vehicle **2** can not only move forward, backward or sideways or along curves, but it can for example also rotate around an arbitrary vertically oriented axis.

The mobile robot **1** comprises a robot arm **6**, which is implemented as serial kinematics and has several members arranged one after the other, which are connected to joints, so that the individual members are, with respect to the axes of rotation, mounted pivotably relative to each other.

In the case of the present implementation, the robot arm **6** has five degrees of freedom and comprises a first member **11**, a second member **12**, a third member **13**, a fourth member **14**, a fifth member **15** and a sixth member **16** and a first axis of rotation **21**, a second axis of rotation **22**, a third axis of rotation **23**, a fourth axis of rotation **24** and a fifth axis of rotation **25**.

In the case of the present implementation example, the first axis of rotation **21** and the second axis of rotation **22** are horizontal. The second member **12** is in particular a boom and is, relative to the first member **11**, pivotably mounted with respect to the first axis of rotation **21**.

The second member **12** is followed by the third member **13**. The third member **13** is, relative to the second member **12**, pivotably mounted with respect to the second axis of rotation **22**.

In the case of the present embodiment example, the fourth member **14** is, relative to the third member **13**, pivotably mounted with respect to the third axis of rotation **23**. The third axis of rotation **23** is perpendicular to the second axis of rotation **22**. The fourth member **14** may comprise a fixing device for fixing a tool **7**. However, in the case of the present implementation example, the tool **7** is part of the fourth member **14**. The fourth member **14** is one of the ends of the robot arm **6**.

It is also possible that the robot arm **6** does not include the fourth member **14**, and that the third member **13** comprises the fastening device or the tool **7**. In this case, the third member **13** serves as one of the ends of the robot arm **6**.

The first member **11**, which is in particular a rocker of the robot arm **6**, is arranged preceding the fifth member **15**. The first member **11** is, relative to the fifth member **15**, mounted pivotably relative to the fourth axis of rotation **24**. The fourth axis of rotation is horizontal.

The sixth member **16** is in particular a rack of the robot arm **6**, with which the robot arm **7** is fastened to the vehicle frame **3**. The rack forms one of the ends of the robot arm **6**. However, it is also possible that the carrier vehicle **2** forms the rack, i.e. the sixth member **16**.

The fifth member **15** is in particular a carousel, which, relative to the rack, is pivotably mounted around the fifth axis of rotation **25**. The fifth axis of rotation is vertical.

In the case of the present embodiment example, the carrier vehicle **2** is omnidirectionally movable, which is why the carrier vehicle **2** can also rotate around the fifth axis of rotation **25**. It may also be provided that the first member **11** directly follows the rack, i.e. that it is, relative to the rack, pivotably mounted with respect to the fourth axis of rotation **24**. In this case, the robot arm **7** does not comprise a carousel.

The mobile robot **1** further comprises drives connected to the control device **5**. In the case of the present implementation example, the drives are electric drives, in particular controlled electric drives. At least the motors of these electric drives are arranged in or on the robot arm **6**.

When the robot **1** is in operation, it is provided that the control device **5** controls the drives of the mobile robot **1**, i.e. the drives for moving the members of the robot arm **6** and the drives for moving the wheels **4** in such a way that a so-called tool center point **8** assigned to the robot arm **8** takes a predetermined nominal position where necessary also a nominal orientation in space or rather the tool center point **8** moves automatically on a predetermined path.

In the case of the present implementation, the robot arm **6** has five degrees of freedom. The entire mobile robot **1** thus comprises eight degrees of freedom because the carrier vehicle **2** comprises three degrees of freedom.

The position of the tool **7** or the tool center point **8** can be determined in coordinates of a world coordinate systems K_W shown in FIG. **2**. The world coordinate system K_W Kw is a cartesian coordinate system with the world coordinate axes X_W, Y_W, W_W and an origin U_W. The world coordinate system K_W is stationary.

In the case of the present embodiment, the world coordinate system K_W is defined such that its world coordinates X_W and Y_W span open a plane E_{XY} on which the mobile robot **1** moves. The coordinate of the Z_W world coordinate axis thus yields the height Z of the tool center point **8** of the plane E_{XY}, on which the mobile robot **1** moves.

The orientation of the tool center point **8** can be determined by angular coordinates of the world coordinate system K_W.

Assigned to the tool **7** or rather the tool center point **8**, FIG. **2** also shows a TCP coordinate system K_{TCP} whose origin is in the tool center point **8**. The TCP coordinate system K_{TCP} is a cartesian coordinate system with the TCP coordinate axes X_{TCP}, Y_{TCP}, Z_{TCP}. The Z_{TCP}-TCP coordinate axis is perpendicular to the second axis of rotation **22** or rather extends in the direction of the third axis of rotation **23**, basically "in the impact direction" of tool **7**.

Using the TCP coordinate system K_{TCP}, it is also possible to determine the orientation of the tool center point **8** with respect to the world coordinate system K_W.

In the case of the present implementation example, the TCP coordinate axes Z_{TCP} and the plane E_{XY} enclose an angle β.

In the case of the present implementation example, for example, an automatic movement of the tool **7** or the tool center points **8** along the height Z at a fixed position in the plane E_{XY} determined by the X_W and Y_W world coordinate axes of the world coordinate system K_W is to be planned, preferable offline. The height Z corresponds to the Z_W world coordinate of the world coordinate system K_W.

In the case of the present implementation example, for this plan, the positions and orientations of the tool center points **8** with respect to the world coordinate system K_W are transformed into a two-dimensional subspace, whose coordinates are the height Z of the tool center point **8** and the angle β.

As already mentioned, the mobile robot has eight degrees of freedom. The mobile robot **1** is a redundant mobile robot, for which there are generally several possible configurations of the mobile robot **1** for the respective positions and orientations of the tool center point in space, i.e. several possible positions of the robot arm **6** and several possible positions and orientations of the carrier vehicle **2** within the plane E_{XY}. The positions of the robot arm **6** arise from the angular positions of the individual members relative to each other.

It is thus possible to assign to the individual orientations and positions of the tool center point **8** in space a measure for the possible configurations of the mobile robot **1**, depending on the height Z and the angle β. In the following this is referred to as redundancy P. A redundancy P can thus be respectively assigned to certain pairs (Z; β).

In the case of the present implementation example, the operation of the mobile robot **1** is planned with the aid of at least one graph, in which the redundancy P is represented as a function of the height Z and the angle β.

FIG. **3** shows how the height Z, the angle β and the redundancy P can in particular form a three-dimensional coordinate system **30**, in which, in a first graph G**1**, the redundancy P is shown as a function of the height Z and the angle β. The first graph G**1** is a three-dimensional graph. The greater the value of the redundancy P, the greater is the number of possible configurations of the mobile robot **1**, in which the tool center point **8** can assume a certain height Z with a certain angle β. The height Z may, for example, be entered as a normalized value, for which Z=1.0 is the maximum height which the tool center point **8** can reach due to the geometric extension of the mobile robot **1**.

To illustrate the first graph G**1** even more, the latter can be color-marked, whereby (Z; β) pairs with a higher redundancy P are color-marked differently from (Z; β) pairs with lower redundancy P. (Z; β) pairs for which there are no possible configurations because of the the spatial extension of the robot **1**, can be marked in another color.

The height Z, the angle β and the redundancy P can be illustrated as a two-dimensional graph (second graph G**2**) as shown in FIG. **4**. The second graph G**2** shows the height Z as a function of the angle β. To visualize the redundancy P, the second graph G**2** is marked differently, for example by using different colors or different grayscales to visualize the redundancy P.

The second graph G**2** is in particular a plan view of the first graph G**1**. In the second graph G**2** it is relatively easy to determine possible (Z; β) pairs or (Z; β) pairs with relatively high redundancy P.

The second graph G**2** comprises, for example, first areas **41**, to which (Z; β) pairs are assigned, for which no configurations of the mobile robot **1** are possible, second areas **42**, to which (Z; β) pairs are assigned, for which configuration of the mobile robot **1** with relatively low redundancy P are possible, and third areas **43**, to which (Z; β) pairs are assigned, for which configurations of the mobile robot **1** with relatively high redundancy P are possible.

FIGS. **5** and **6** illustrate how, based on the second graph G**2**, it can be checked whether the trajectory of a planned path for the tool center point **8** can be performed with the mobile robot **1**.

First, the trajectory **51** of a path is planned in six-dimensional space, along which the tool center point **8** is to move automatically. The trajectory **51** of the path in six-dimensional space is planned, for example, in world coordinates or in world and TCP coordinates, and comprises information about the course of the position and orientation of the tool center point **8** in space.

Next, the trajectory **51** of the planned path is transformed into the two-dimensional subspace by means of a transformation **52**, whereby a transformed path is created, whose trajectory **53** can be represented graphically.

Next, the graphic trajectory **53** of the transformed planned path is superimposed on the second graph G**2**.

If the trajectory **51** of the planned path can be followed by the mobile robot **1**, then the trajectory **53** of the transformed planned path is located within areas of the second graph G**2**, to which (Z; β) pairs are assigned, for which a configuration of the mobile robot **1** is possible. Such a case is shown in FIG. **5**.

If the trajectory **51** of the planned path cannot be followed by the mobile robot **1**, then the trajectory **53** of the transformed planned path is at least partly located within areas of the second graph G**2**, to which (Z; β) pairs are assigned, for which a configuration of the mobile robot **1** is impossible. Such a case is shown in FIG. **6**.

If the trajectory **51** of the planned path cannot be followed by the mobile robot **1**, then the trajectory **53** of the transformed planned path can be altered, so that a revised trajectory **73** of the transformed path is created, which can be followed by robot **1**. This is illustrated in FIG. **7**. The revised trajectory **53** of the transformed planned path is changed in the superimposed second graph G**2**, in order to be able to directly determine whether the revised trajectory **73** of the transformed planned path can be followed with the mobile robot **1**. The trajectory of the transformed path can be changed, for example, by means of a cursor.

Next, the revised trajectory **73** of the transformed planned path is, by means of an inverse retransformation **72**, transformed from the two-dimensional subspace back to the six-dimensional space, whereby a modified planned path is created, whose trajectory is marked by reference symbol **71** shown in FIG. **7** (revised trajectory **71** of the planned path). The mobile robot **1** can be correspondingly programmed on the basis of the revised planned path.

FIG. **8** illustrates an example of a configuration plan of the mobile robot **1**, where the tool center point **8** is to assume a predetermined height Z. Due to the redundancy P, multiple angles **13** arise for this height Z. FIG. **8** shows the mobile robot **1** for three configurations of the mobile robot **1**, in which the tool center point **8** assumes the same height Z, but with respectively different angles β.

In the example shown in FIG. **8**, the carrier vehicle **2** assumes the same position and orientation for two configurations of the mobile robot **1**, the angle settings of the members of the robot arm **6** differ relatively to each other. For these two configurations of the mobile robot **1**, the carrier vehicle **2** is represented by solid lines and the robot arm **6** for a first configuration of the mobile robot **1** is also represented by a solid line, and for a second configuration of the mobile robot **1** by a dashed line.

The mobile robot **1** is represented by a dotted-dashed line for the third configuration of the mobile robot **1**.

A value of β1 is obtained for the angle β for the first configuration of the mobile robot **1**, a value of β2 is obtained for the angle β for the second configuration of the mobile robot **1**, and a value of β3 is obtained for the angle β for the third configuration of the mobile robot **1**. In FIG. **4**, these values β1, β2, β3 are also shown in the first graph G**1** and the second graph G**2**, so that one person can read the corresponding redundancies P for each of the angles β.

At a given height Z for gripping a workpiece with a tool **7** designed as a gripping device, there are several angles β for this gripper position. Due to the redundancy of the mobile robot **1**, there are more favorable and less favorable configurations of the mobile robot **1**, to which an angle β is assigned. By means of graphs G**1** and G**2** it is possible to compare different values of the angle β for the predetermined height Z with reference to the redundancy P.

With the help of graphs G**1** and/or G**2** it is thus possible to perform the following method:

First, height Z of the tool center point is 8 is determined.

Next, the first graph G**1** and/or the second graph G**2** are used to determine possible values β1, β2, β3 of angle β. This can also be done in an automated process.

Next, that value of β1, β2, β3 of angle β is determined, to which the highest redundancy P has been assigned. Thus a pair (Z; β) is obtained, which is used for planning the movement of the mobile robot **1**.

Alternatively, it is also possible to predetermine an angle β, in order to determine for this angle β the height to which the highest redundancy has been assigned. Thus a pair (Z; β) is obtained, which is used for planning the movement of the mobile robot **1**.

Using graphs G**1** and G**2** it is also possible to plan the following task for the mobile robot **1**: The mobile robot **1** is to use a tool **7** embodied as a gripper to grip a workpiece and place it in another position. Graphs G**1** and/or G**2** can be used to determine favorable positions for this task.

While the present invention has been illustrated by a description of various embodiments, and while these embodiments have been described in considerable detail, it is not intended to restrict or in any way limit the scope of the appended claims to such detail. The various features shown and described herein may be used alone or in any combination. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative apparatus and method, and illustrative example shown and described. Accordingly, departures may be made from such details without departing from the spirit and scope of the general inventive concept.

What is claimed is:

1. A method for the redundancy-optimized planning of the operation of a redundant mobile robot, the mobile robot comprising a mobile carrier vehicle, a robot arm with a plurality of links connected by joints that pivotally mount the links with respect to axes of rotation, drives for moving the links relative to each other, and an electronic control device which is configured to control the drives for the links and the carrier vehicle for the movement of the mobile robot, the method comprising:

assigning a tool center point (TCP) of the robot arm to a TCP coordinate system having a first TCP-coordinate axis, a second TCP coordinate axis, and a third TCP coordinate axis;

identifying a Cartesian world coordinate system with a first world coordinate axis, a second world coordinate axis, and a third world coordinate axis;

wherein the first world coordinate axis and the second world coordinate axis span a plane on which the mobile robot moves, a height of the tool center point from the plane is defined along the third world coordinate axis, and the orientation of the tool center point is defined by an angle between the plane and one of the TCP coordinate axes;

creating at least one graph in which a redundancy of the robot is presented as a function of the height and the angle, wherein the redundancy is a measure of possible configurations of the mobile robot depending on the height and the angle;

planning an operation of the mobile robot with the help of the at least one graph;

wherein the at least one graph is a second graph in which the height is presented as a function of the angle, and the redundancy in the second graph is differently marked to present the redundancy as a function of the height and the angle;

planning a trajectory of a path in six-dimensional space along which the tool center point is to move automatically;

transforming the trajectory of the planned path in a two-dimensional subspace, whereby the trajectory of a transformed path is created, whereby the subspace represents the planned position and orientation of the tool center point in terms of the height and the angle;

overlaying the trajectory of the transformed planned path with the second graph; and

on the basis of the superimposed trajectory of the transformed path with the second graph, determining whether the planned trajectory can be followed by the mobile robot.

2. The method of claim **1**, wherein:

the robot arm has five degrees of freedom and includes a first link, a second link, a third link, a fourth link, a fifth link, and includes a sixth link, and as axes of rotation a first axis of rotation, a second axis of rotation, a third axis of rotation, a fourth axis of rotation, and a fifth axis of rotation;

the first axis of rotation, the second axis of rotation, and the fourth axis of rotation are horizontal, and the fifth axis of rotation is vertical;

the second link is pivotably mounted relative to the first link with respect to the first axis of rotation;

the second link is followed by the third link;

the third link is pivotably mounted relative to the second link with respect to the second axis of rotation;

the fourth link is pivotably mounted relative to the third link with respect to the third axis of rotation, which is perpendicular to the second axis of rotation;

the fourth link comprises a tool or a fastening device for fastening a tool;

the sixth link is immovably attached to the carrier vehicle or represents the carrier vehicle;

the fifth link is pivotably mounted relative to the sixth link with respect to the fifth axis of rotation;

the first link is pivotably mounted relative to the fifth link with respect to the fourth axis of rotation; and

the third TCP coordinate axis runs in the direction of the third axis of rotation and encloses the angle made with the plane.

3. The method of claim **1**, wherein:

the robot arm has four degrees of freedom and includes a first link, a second link, a third link, a fourth link, and a fifth link, and includes a first axis of rotation, a second axis of rotation, a third axis of rotation, and a fourth axis of rotation;

the first axis of rotation, the second axis of rotation, and the fourth axis of rotation are horizontal;

the second link is pivotably mounted relative to the first link with respect to the first axis of rotation;

the second link is followed by the third link;

the third link is pivotably mounted relative to the second link with respect to the second axis of rotation;

the fourth link is pivotably mounted relative to the third link with respect to the third axis of rotation, which is perpendicular to the second axis of rotation;

the fourth link comprises a tool or a fastening device for fastening a tool;

the fifth link is immovably attached to the carrier vehicle or represents the carrier vehicle; and the third TCP coordinate axis runs in the direction of the third axis of rotation and encloses the angle made with the plane.

4. The method of claim **1**, wherein at least one of:

the carrier vehicle comprises wheels and drives for driving the wheels and the electronic device is configured to control the drives to move the carrier vehicle; or

the carrier vehicle is embodied as an omnidirectionally movable carrier vehicle.

5. The method of claim **1**, wherein the at least one graph is a first graph, whereby the height, the angle, and the redundancy form a three-dimensional Cartesian coordinate system such that the redundancy is mapped out as a function of the height and the angle of the first graph.

6. The method of claim **5**, wherein the redundancy in the first graph is marked with different colors or in grayscales.

7. The method of claim **1**, wherein the at least one graph is a second graph in which the height is presented as a function of the angle, and the redundancy in the second graph is differently marked to present the redundancy as a function of the height and the angle.

8. The method of claim **7**, wherein the differently marked graph comprises colors or grayscales.

9. The method of claim **1**, further comprising:

altering the trajectory of the transformed planned path within the overlayed second graph when the planned path cannot be followed by the mobile robot **1**, such that a revised trajectory of the transformed planned path is formed which can be followed by the mobile robot; and

creating a revised planned trajectory in six-dimensional space based on the revised trajectory of the transformed planned path.

10. The method of claim **1**, wherein:

the tool is a gripper with which the mobile robot grips a workpiece and places the workpiece in a different position; and

the at least one graph is used to determine favorable positions for placing the workpiece in a different position.

11. A method for the redundancy-optimized planning of the operation of a redundant mobile robot, the mobile robot comprising a mobile carrier vehicle, a robot arm with a plurality of links connected by joints that pivotally mount the links with respect to axes of rotation, drives for moving the links relative to each other, and an electronic control device which is configured to control the drives for the links and the carrier vehicle for the movement of the mobile robot, the method comprising:

assigning a tool center point (TCP) of the robot arm to a TCP coordinate system having a first TCP-coordinate axis, a second TCP coordinate axis, and a third TCP coordinate axis;

identifying a Cartesian world coordinate system with a first world coordinate axis, a second world coordinate axis, and a third world coordinate axis;

wherein the first world coordinate axis and the second world coordinate axis span a plane on which the mobile robot moves, a height of the tool center point from the plane is defined along the third world coordinate axis, and the orientation of the tool center point is defined by an angle between the plane and one of the TCP coordinate axes;

creating at least one graph in which a redundancy of the robot is presented as a function of the height and the angle, wherein the redundancy is a measure of possible configurations of the mobile robot depending on the height and the angle;

planning an operation of the mobile robot with the help of the at least one graph;

wherein the at least one graph is a first graph, whereby the height, the angle, and the redundancy form a three-dimensional Cartesian coordinate system such that the redundancy is mapped out as a function of the height and the angle of the first graph;

selecting a height for the tool center point;

determining possible values of the angle with the help of at least one of the first graph or a second graph in which the height is presented as a function of the angle, and the redundancy in the second graph is differently marked to present the redundancy as a function of the height and the angle;

determining the value of the angle to which the highest redundancy is assigned; and

using the determined value of the angle for planning the movement of the mobile robot.

12. A method for the redundancy-optimized planning of the operation of a redundant mobile robot, the mobile robot comprising a mobile carrier vehicle, a robot arm with a plurality of links connected by joints that pivotally mount the links with respect to axes of rotation, drives for moving the links relative to each other, and an electronic control device which is configured to control the drives for the links and the carrier vehicle for the movement of the mobile robot, the method comprising:

assigning a tool center point (TCP) of the robot arm to a TCP coordinate system having a first TCP-coordinate axis, a second TCP coordinate axis, and a third TCP coordinate axis;

identifying a Cartesian world coordinate system with a first world coordinate axis, a second world coordinate axis, and a third world coordinate axis;

wherein the first world coordinate axis and the second world coordinate axis span a plane on which the mobile robot moves, a height of the tool center point from the plane is defined along the third world coordinate axis, and the orientation of the tool center point is defined by an angle between the plane and one of the TCP coordinate axes;

creating at least one graph in which a redundancy of the robot is presented as a function of the height and the angle, wherein the redundancy is a measure of possible configurations of the mobile robot depending on the height and the angle;

planning an operation of the mobile robot with the help of the at least one graph;

wherein the at least one graph is a first graph, whereby the height, the angle, and the redundancy form a three-dimensional Cartesian coordinate system such that the redundancy is mapped out as a function of the height and the angle of the first graph;

selecting the angle;

determining possible values of the height with the help of at least one of the first graph or a second graph in which the height is presented as a function of the angle, and the redundancy in the second graph is differently marked to present the redundancy as a function of the height and the angle;

determining the value of the height to which the highest redundancy is assigned; and using the determined value of the height for planning the movement of the mobile robot.

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